1 NTERFEROMETRIC SYNTHETIC APERTURE RADAR IMAGERY OF THE GULF STREAM

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1. INTRODUCTION

The advent of interferometric synthetic aperture radar (INSAR) imagery brought to the ocean remote sensing field techniques used in radio astronomy. Whilst details of the interferometry differ between tile two fields, the basic idea is the same: Use the phase information arising from positional differences of the radar recievers and/or transmitters to probe remote structures. The success of airborne INSAR methods (Goldstein *et al.*, 1987) provided ample incentive to investigate numerous other applications, e.g. topographic mapping (Zebker *et al.*, *1986),* surface ocean currents (Goldstein *et al.*, *1987)* and internal waves (Thompson *et al.*, 1993). A primary advantage of the INSAR technique when applied to ocean surfaces is the ability to observe the motion of surface scatterers.

The interferometric image is formed from two complex synthetic aperture radar (SAR) images. These two images are of the same area but separated in time. Typically the time between these images is very short - approximately 50 msec. During this short period the radar scatterers on the ocean surface do not have time to significantly decorrelate. Hence the two SAR images will nave the same amplitude, since both measure the radar reflection from essentially the same object. Although the ocean surface structure does not significantly decorrelate in 50 msec., surface features do have time to move. It is precisely the translation of scattering features across the ocean surface which gives rise to phase differences between the two SAR images. This phase difference is directly proportional to the range velocity of surface scatterers. The constant of proportionality is dependent upon the interferometer. The total phase difference between the two SAR images is then

$$\Delta\phi = -\frac{2\pi\ell}{v_{air}\lambda} u_{range} ,$$

where ℓ is the spacing between the radar recievers (the baseline of the interferometer), λ is the radar wavelength, v_{air} is the aircraft velocity and u_{range} is the component of the scatterer's velocity in the range direction. The motion of the scatterers may arise from ocean currents, internal wave motions, winds or most generally all of the above. Idnetifying these different components of u_{range}, without recourse to additional information, is a formidable task.

One immediately sees several possible limitations to the INSAR technique. The time between images must be short enough that the ocean surface does riot

decorrelate, otherwise the phase difference contains no new information. Also the time between images must be long enough so that the surface features have time to move and thus Provide a phase difference. We implicitly require that the SAR images have been corrected for the aircraft sidewards drift and yaw, both of which will produce (unwanted) phase differences. Therefore as a practical matter the phase difference arising from the surface motion should be greater than the errors in compensating for aircraft motion - the signal-to-noise ratio should be large. Perhaps more irksome than the above is the problem of large surface velocities, when the phase difference is greater than 2π. The interferometric image determines the phase differences modulo 2π, therefore many velocities map onto the same phase difference. Typically, range velocities of scatterers of approximately 0.0 m/sec., 2.7 m/sec., 5.4 m/see., etc. all yield a zero phase difference in the interferometric image. One possible means of lifting this phase ambiguity is to use multi-frequency arid/or multi-baseline interferometry. These methods have been discussed by Carande, 1992 and Carande *et al.*, 1991. Therefore the interpretation of INSAR images may require other information, additional assumptions and/or modeling.

2. GULF STREAM IMAGES

The particular interferometric images which we have analysed are from the 1990 AIRSAR flight of July 20th, previously idnetified as G-Stream NI-060-1 (Kobrick, 1990; Valenzuela *et al.*, 1991). The complex interferometric image is the product of one complex SAR image with the complex conjugate of the other. '] 'herefore the amplitude of the INSAR image is the product of the individual SAR image amplitudes. The phase of the INSAR image is the phase difference (modulo 2π) between the two SA R images. The amplitude and phase of the INSA R image are shown in Figure 1. The amplitude image shows no detailed structure and provides only hints of large features. In contrast the phase image clearly depicts the Gulf Stream boundary. The Gulf Stream boundary is the one large feature that may be seen in the amplitude image. In addition, the phase image clearly shows the R/V Cape Henlopen, her wake and other smaller surface strut.ture. We have interpreted the dark- light banding as internal wave motion. The ship is not as visible in the amplitude image owing to the grey-scaling employed to enhance other surface features. The orientation of these images is independently verified by the ship's wake and log she was southbound at 10 knots when the INSAR image was taken.

This comparison of INSAR phase and amplitude images may down-play too much the value of complex SA R imagery. Milman *et al.*, 1990 have developed arid applied ambiguity function techniques to complex SAR images to obtain information about surface velocities. However, the amplitude of SA R images convey no relavant information about velocities and, as seen in Figure 1, little information about s;llall-scale surface features.

The complementary nature of SAR and INSAR images produces a powerful oceanographic remote sensing tool. INSAR is sensitive to surface velocities whereas SAR amplitudes depend strongly on the surface shape. Presumably these two features (shape and velocity) are, in at least some cases, correlated. Therefore employing the additional information which interferometry provides will assist the interpretation of the region surveyed.

3. GROUND TRUTH INFOILMAI'ION AND MODELING

Ground truth information is available in the form of buoy measurements of the wave spectrum and direction. This additional data was obtained at two points
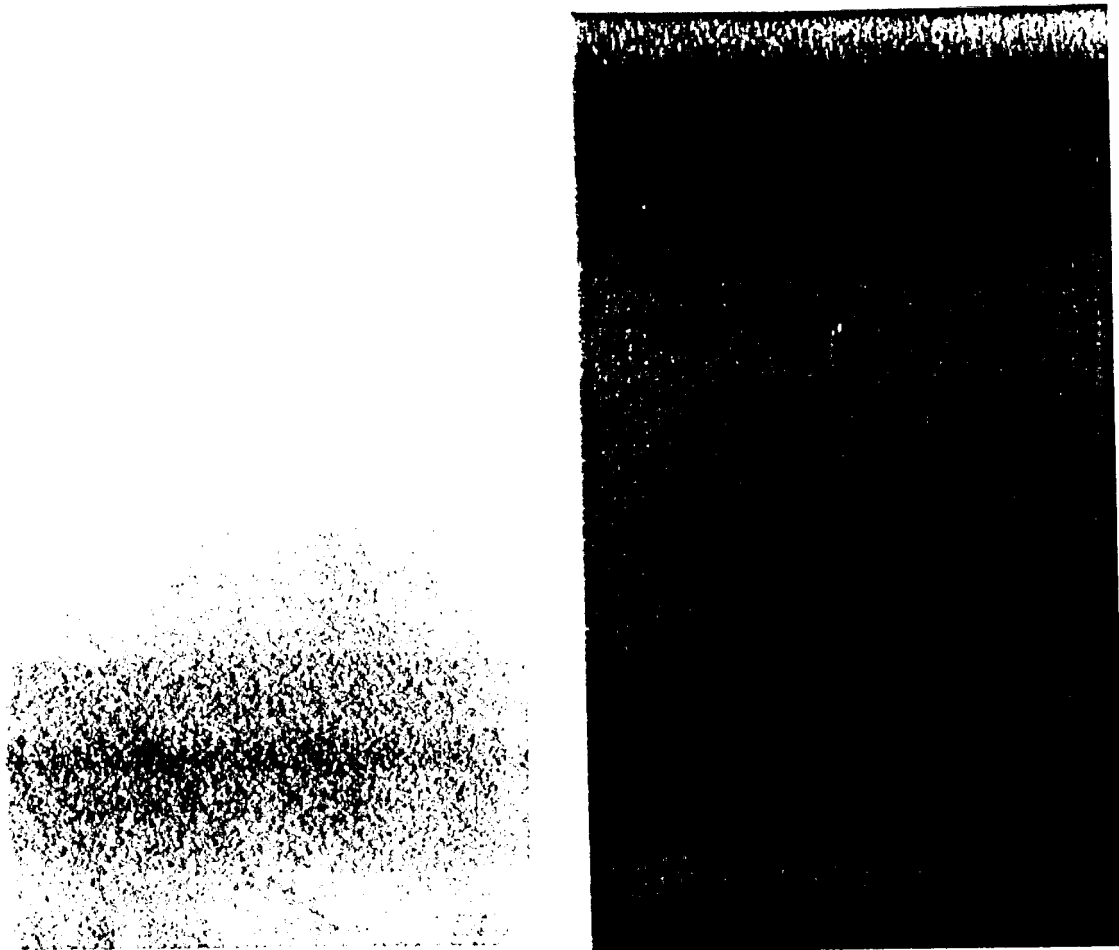
Figure 1: The INSAR amplitude(left) and phase(right) images for run G-Stream NJ- OGO-1 taken July 20, 1990 are displayed. See text for addition discussion.

within the image both before and after taking the INSAR image. We have Fourier analysed the phase image to determine the spectrum of the wave-like structures seen throughout the image. The frequency arrd direction arc directly compared to the buoy data. The Henlopen's wake also may aid in our interpretation of surface features. Thus the available ground truth in conjunction with the INSAR image provides useful constraints for modeling Gulf Stream boundary features.

We are currently modeling both INSAR arid SAR radar return from ocean surfaces. This is an ongoing project and results will be reported at a future date.

4. CONCLUSIONS

Our initial investigation has yielded several interesting characteristics of INSAR imagery: The wave spectrum is clearly seen in the phase image but not in tire amplitude. The boundary of the Gulf Stream is a strong large-scale feature - barely resolved in the amplitude image which dominates the phase image. Similarly, the

4. CONCLUSIONS

Our initial investigation has yielded several interesting characteristics of INSAR imagery: The wave spectrum is clearly seen in the phase image but not in the amplitude. The boundary of the Gulf Stream is a strong linear feature - barely resolved in the amplitude image - which dominates the phase image. Similarly, the Henlopen's wake is easily seen in the phase image. Of course, the snip is clearly resolved in both the amplitude and phase images.

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